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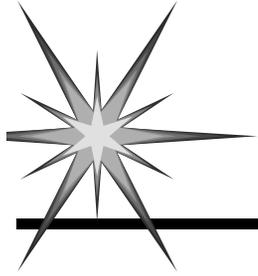
# **Advanced Sensors for Real-time control of Advanced Natural Gas Reciprocating Engine Combustion**

S. H. Sheen, H. T. Chien and A. C. Raptis  
Argonne National laboratory

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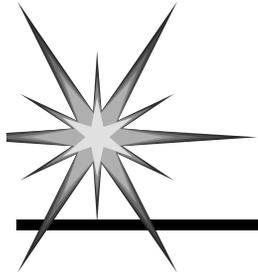


# **ARES Program Goal**

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To develop cleaner and more efficient next generation Natural gas engines that will

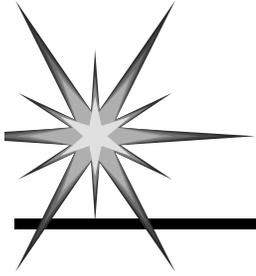
- Increase fuel combustion efficiency
- Reduce emissions of NO<sub>x</sub>, hydrocarbons, air toxics, and greenhouse gases
- Reduce system costs and maintenance frequency



## Typical ARES Engine Exhaust Composition

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• Methane	490 ppm
• Ethane	10 ppm
• Nitric Oxide	200 ppm
• CO	300 ppm
• Hydrogen	150 ppm
• CO <sub>2</sub>	5 %
• H <sub>2</sub> O	10 %
• Oxygen	9 %
• Hydrocarbons	650 ppm
• Nitrogen	Balance

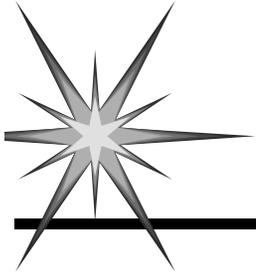


# ANL Project Objectives

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To develop advanced sensors for real-time combustion monitoring of advanced natural-gas reciprocating engines, proposed sensors include:

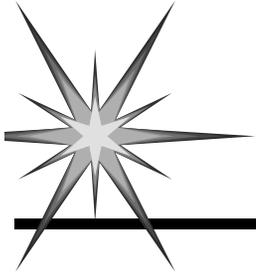
- NOx emission sensor
- Natural-gas composition sensor



# Technical Approaches

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- NO<sub>x</sub> sensor based on ion-mobility spectrometry (IMS)
- Fuel composition sensor based on acoustic techniques, measurements of speed-of-sound, attenuation, and acoustic relaxation spectroscopy

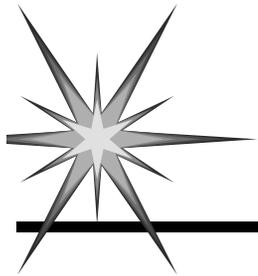


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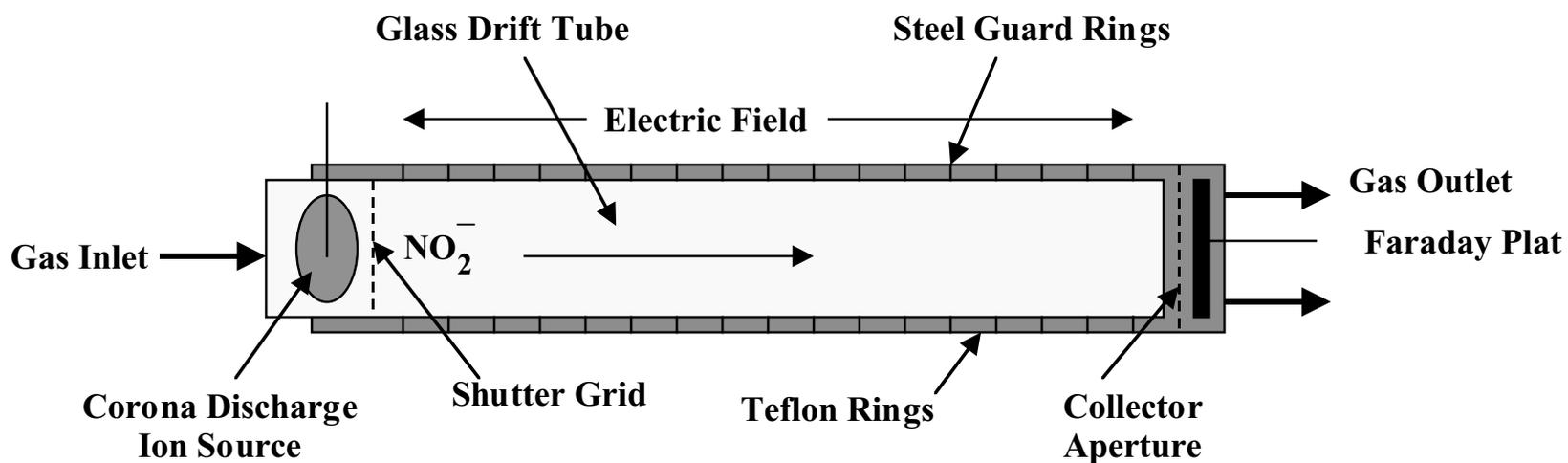
# IMS Sensor for NO<sub>x</sub>

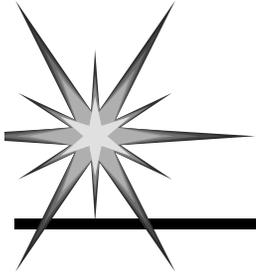
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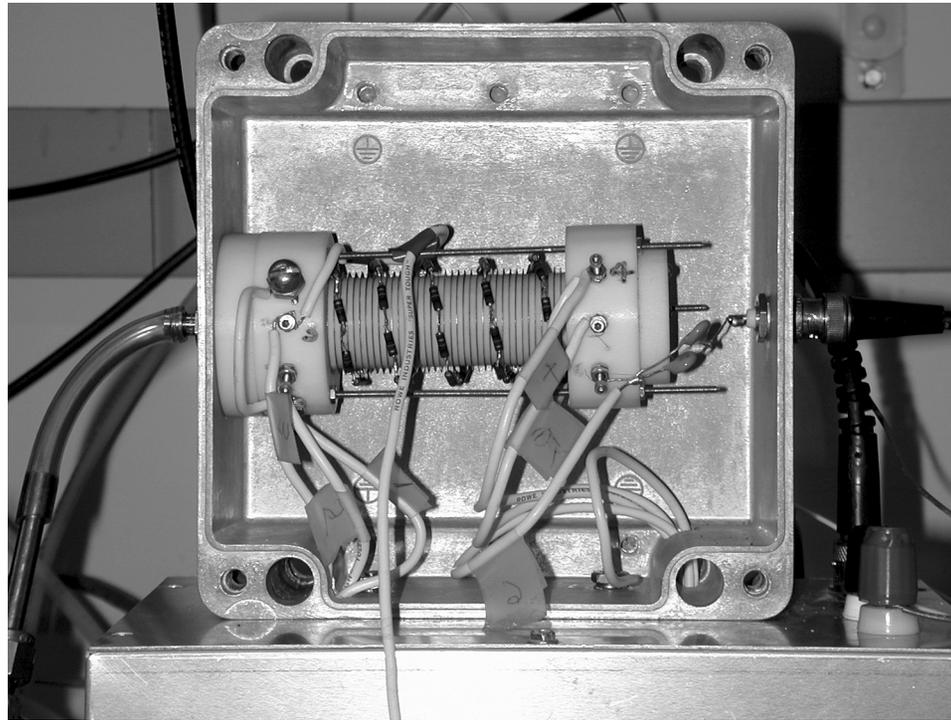
# Basic Design of an IMS





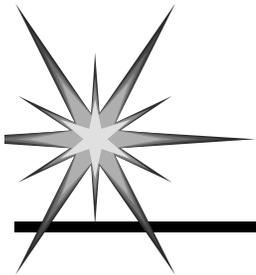
# Laboratory Prototype

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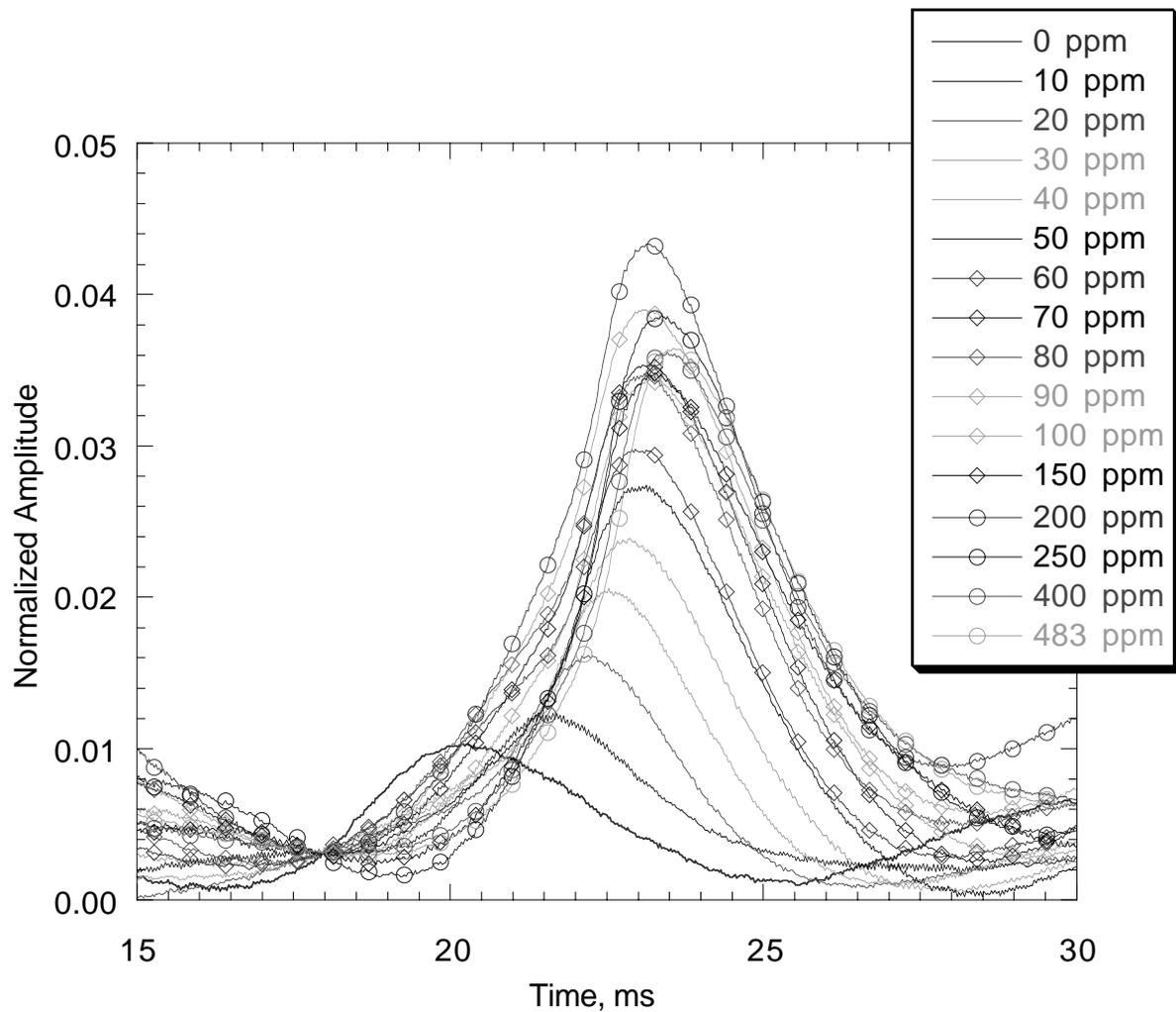
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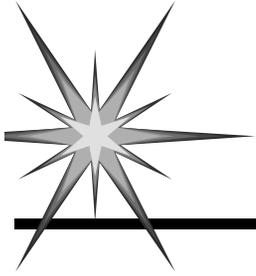
# NO<sub>2</sub> Data from Ni-63 IMS

Normalized at 18 ms, Polarity Reversed, Flow Rate = 2000ml/min

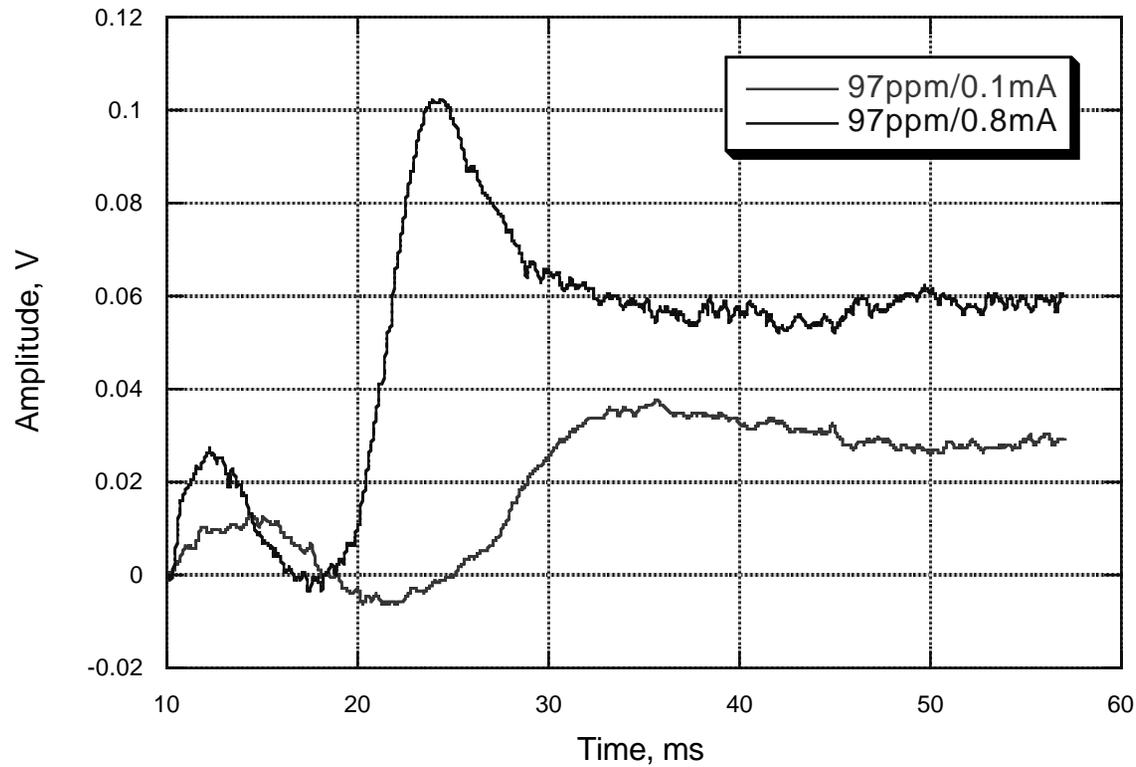


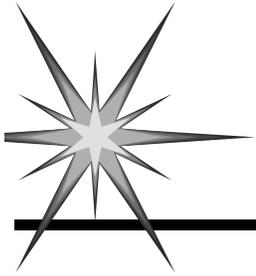
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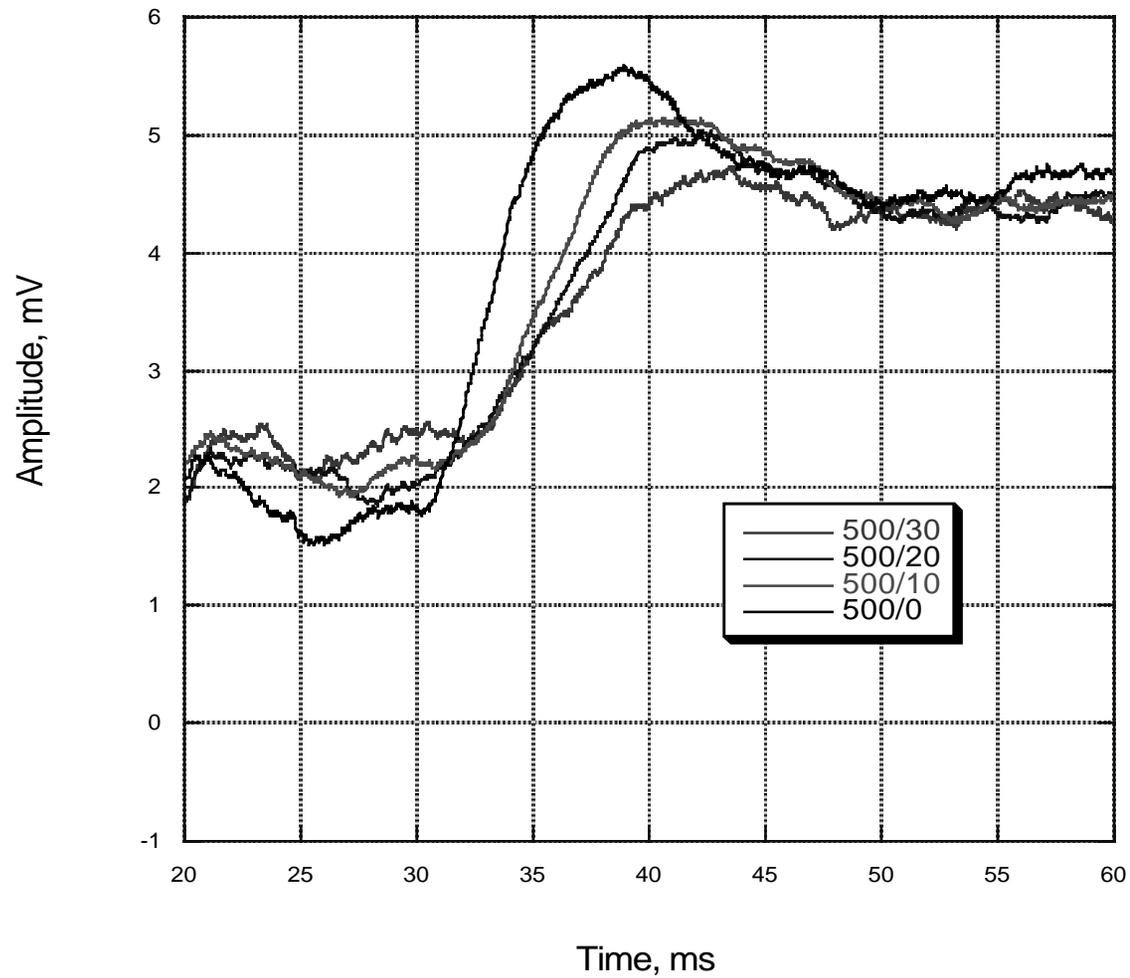


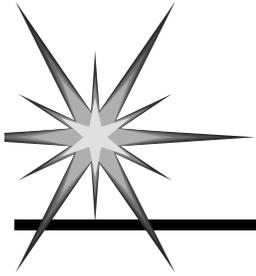
# Corona versus Spark Discharge



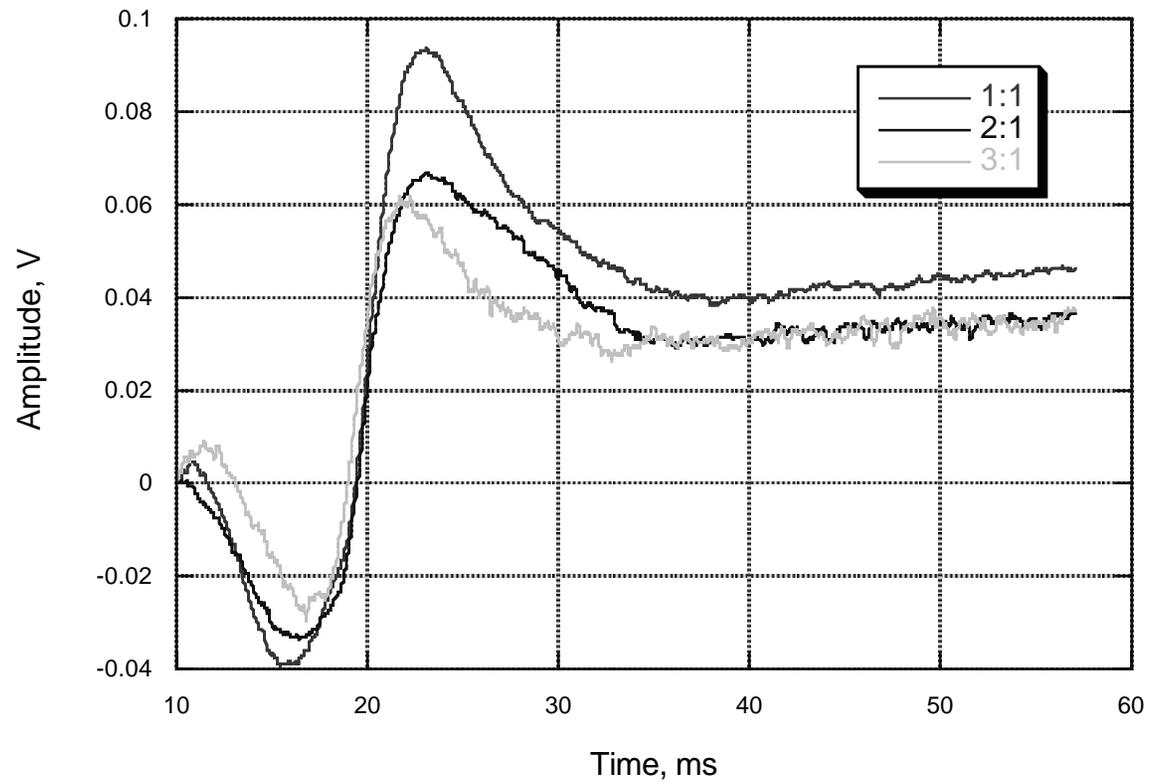


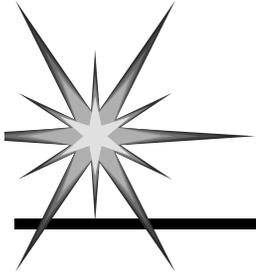
## Corona discharge ion spectra of four NO<sub>2</sub> gas mixtures



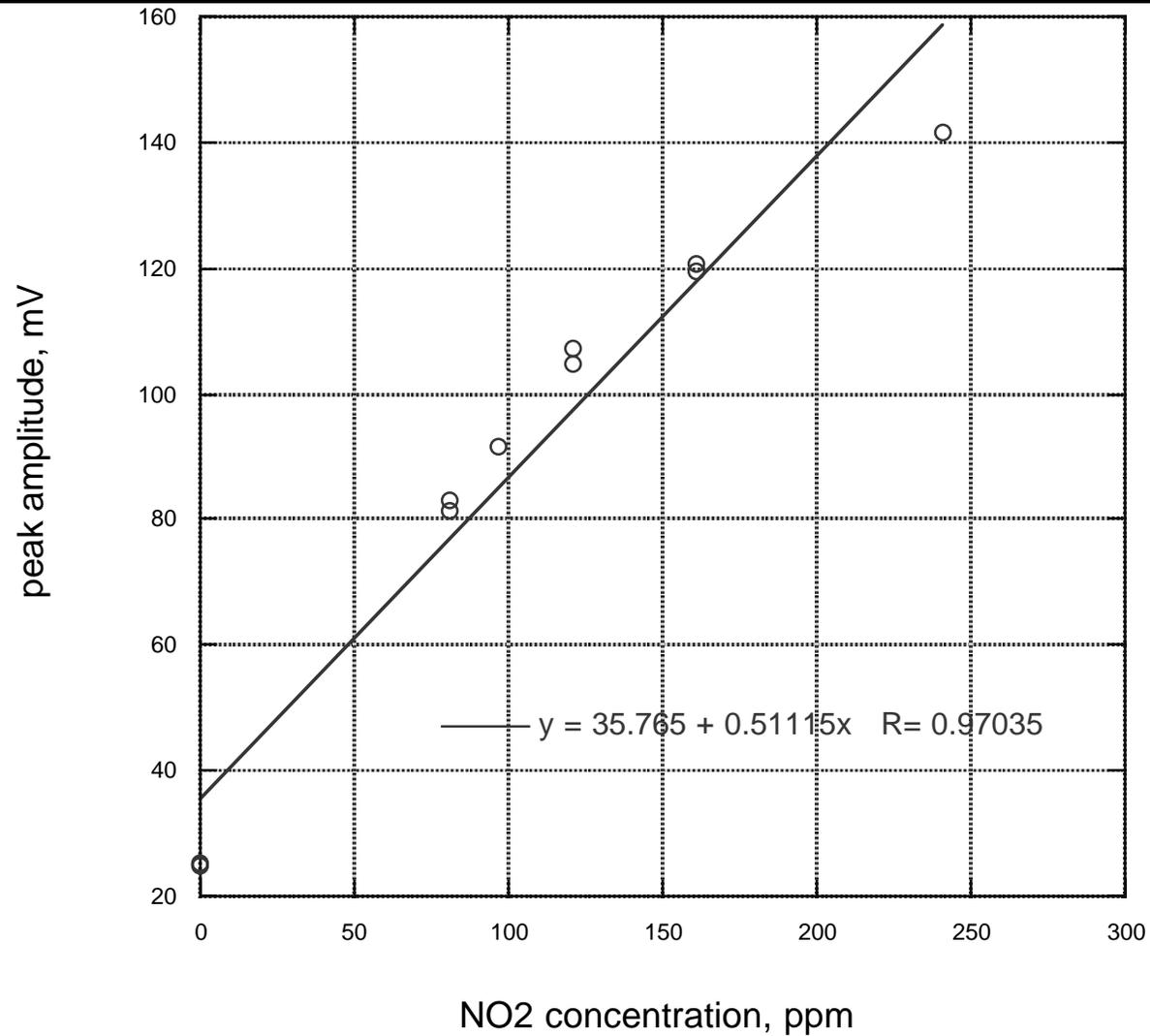


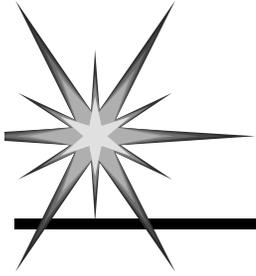
## Spark discharge spectra for three NO<sub>2</sub> gas mixtures



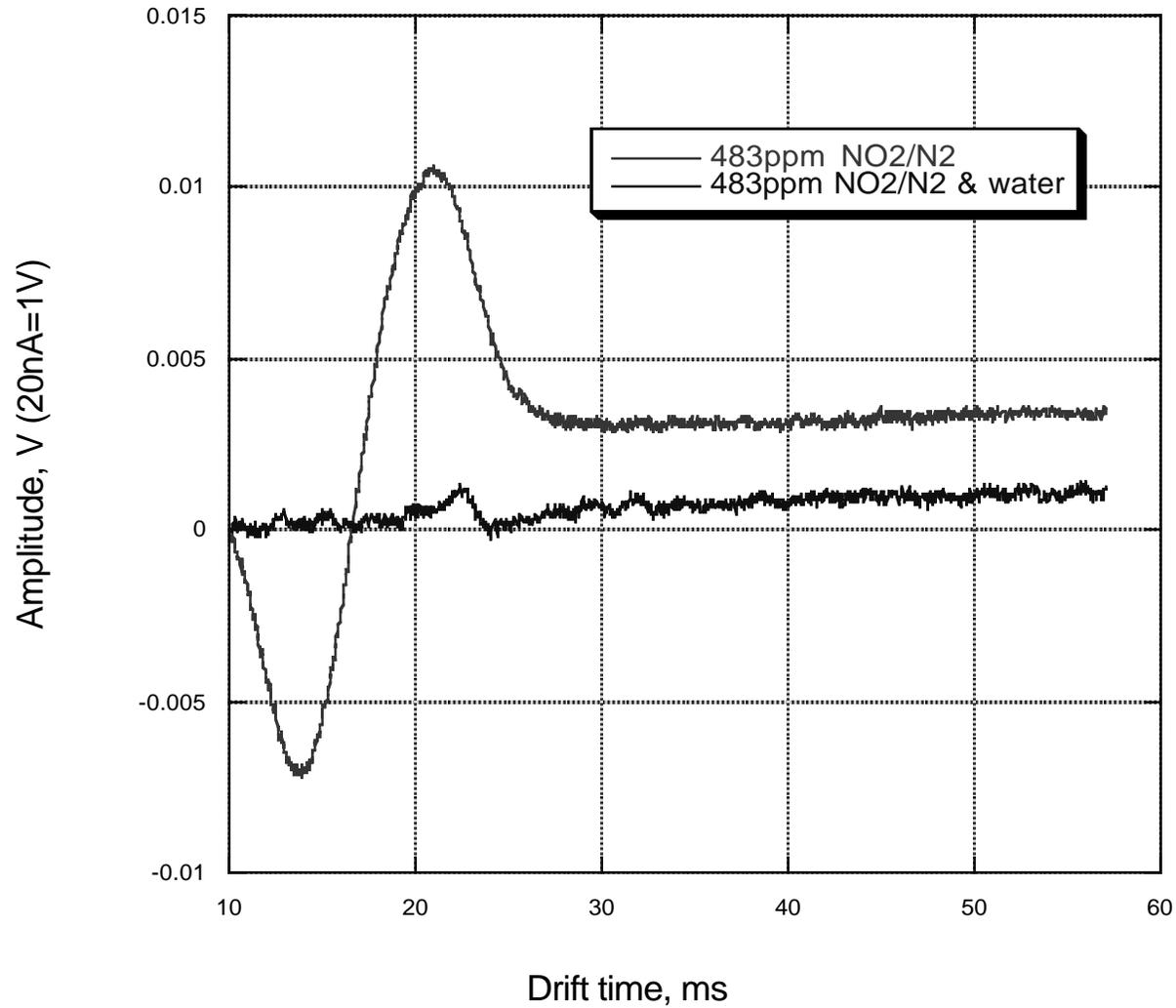


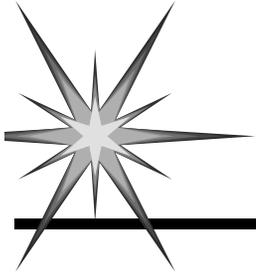
# Linear Fit for Low ppm Data





# Effect of water (3%) on NO<sub>2</sub> ion spectrum



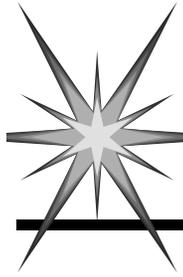


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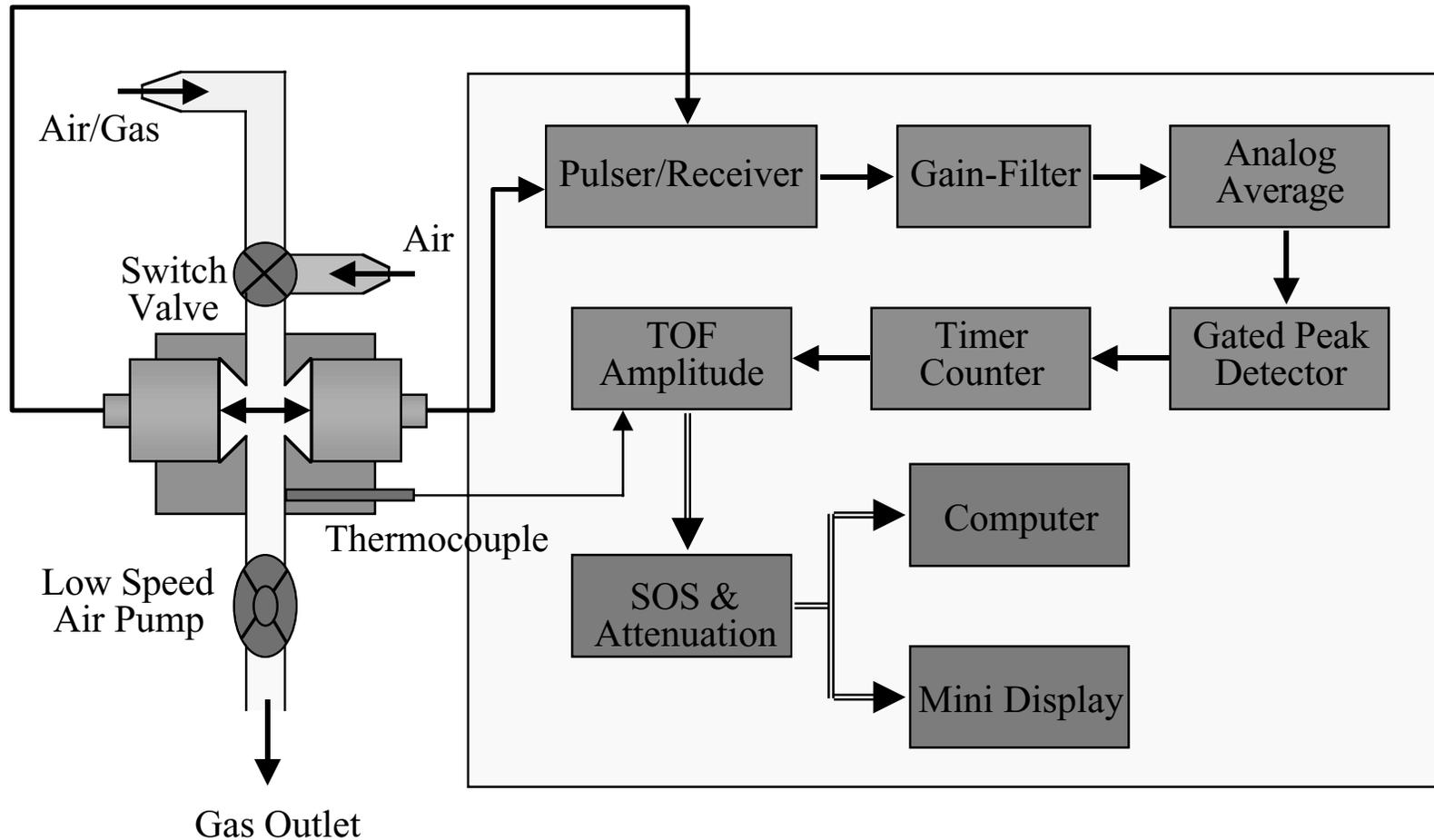
# Acoustic Gas Sensor

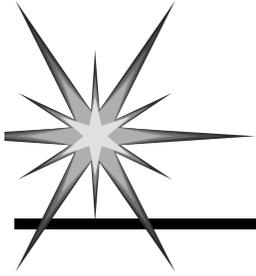
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# Basic Design of SOS Gas Sensor

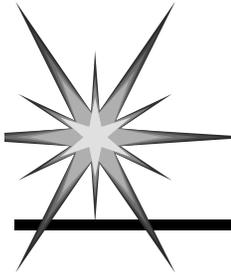




# Special Features of SOS Sensor

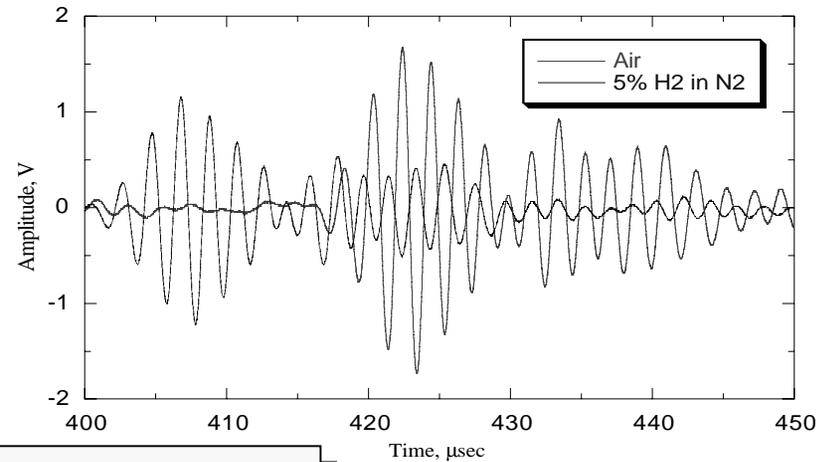
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- Pulse-echo measurement
- Narrow flow channel design
- Higher-order echo analysis
- 0.5 MHz center frequency
- Dual cavity design

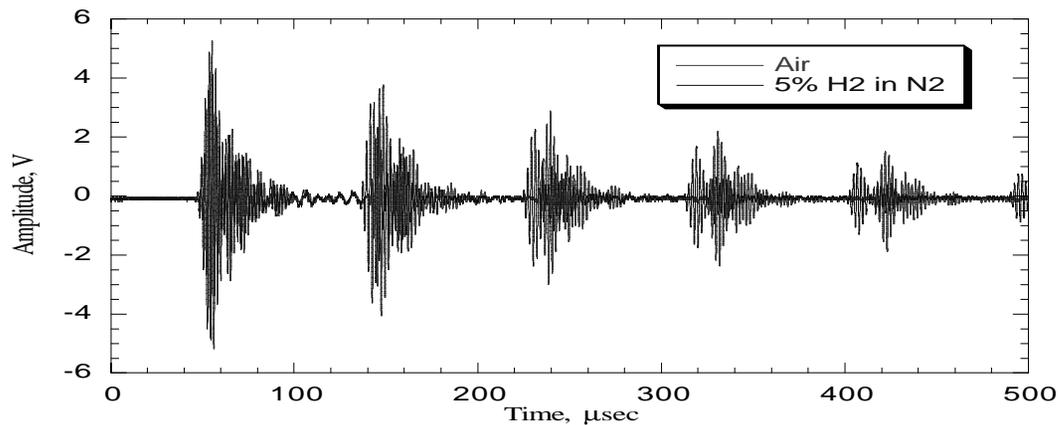


# Ultrasonic Signal for Echoes in Air and 5% Hydrogen in Nitrogen

RF signal for first 5 echoes

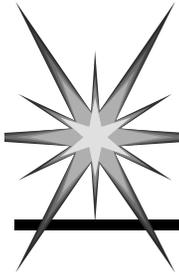


RF signal for 5th echo

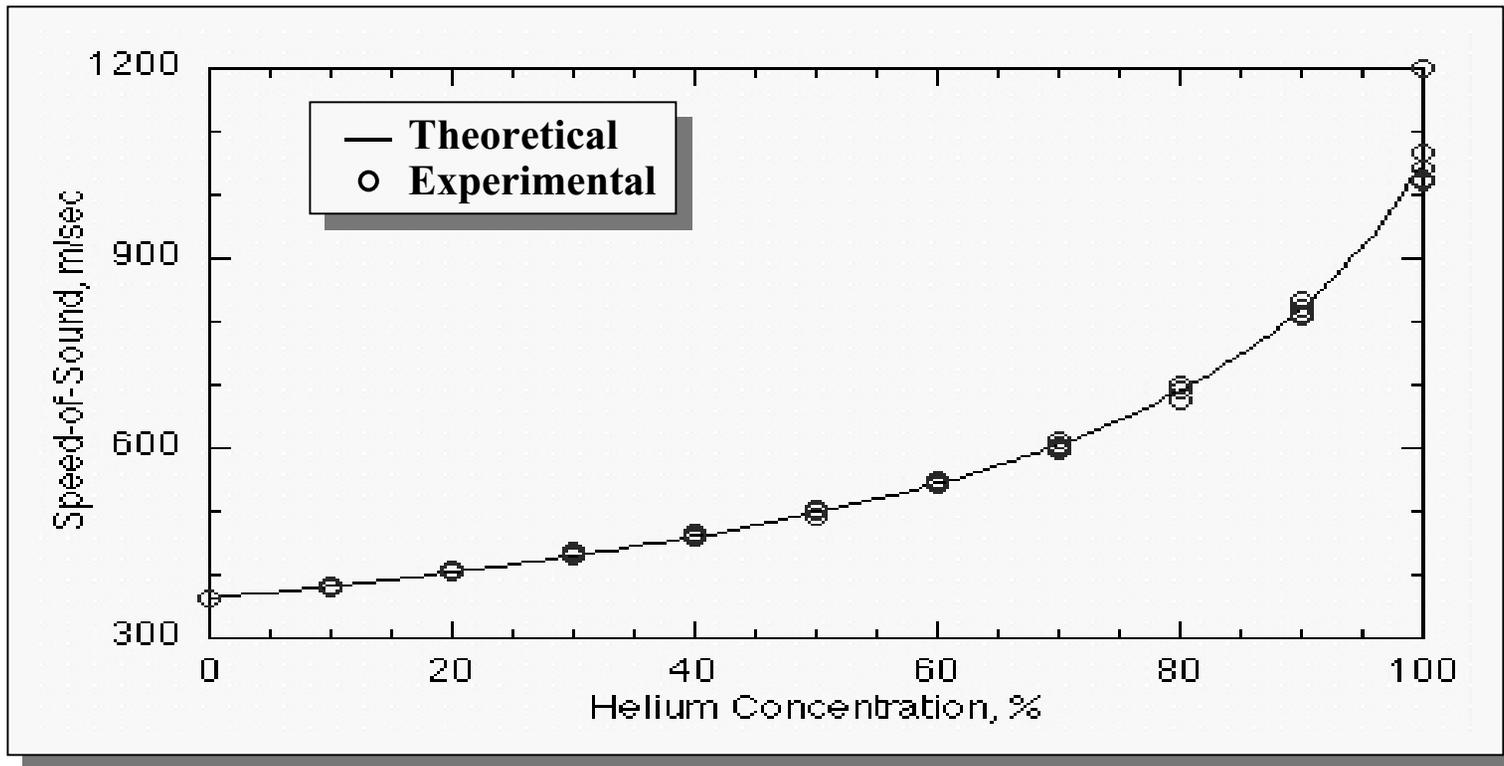


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# Speed-of-Sound (SOS) in a Gas Mixture



$$C = \left[ \frac{RT \sum_{i=1}^n x_i C_{p_i}}{\sum_{i=1}^n x_i M_i \sum_{i=1}^n (x_i C_{p_i} - R)} \right]^{1/2}$$

R: gas constant, T: absolute temperature

$x_i$ : mole fraction of gas i

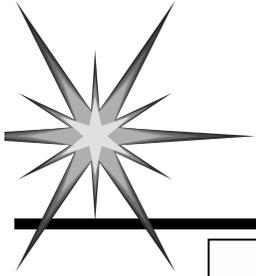
$M_i$ : molecular weight of gas i

$C_{p_i}$ : heat capacity of constant pressure for gas i

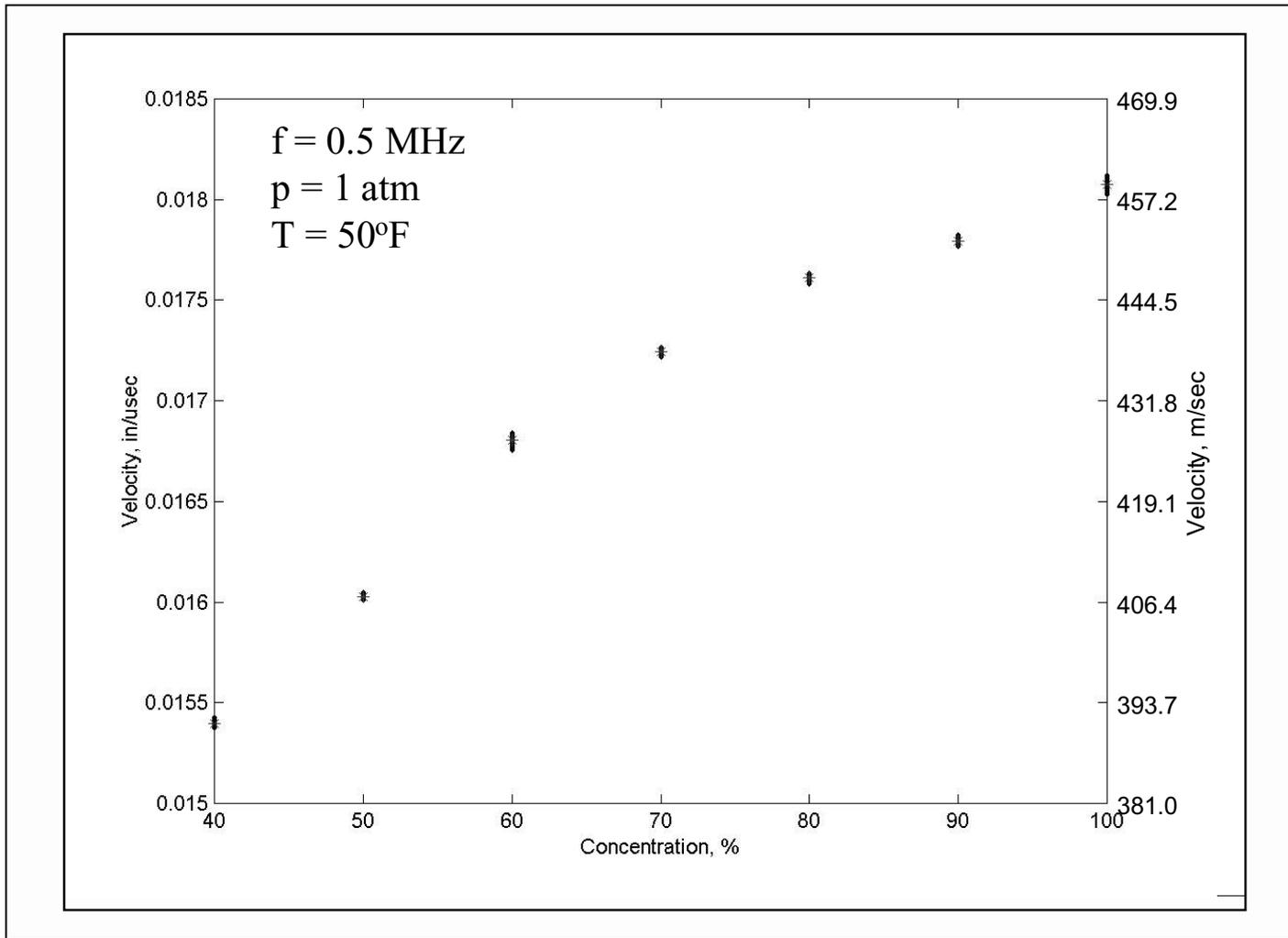
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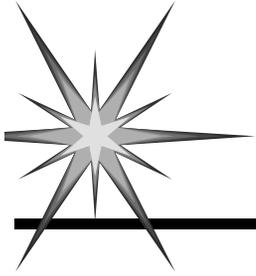






# Speed-of-Sound: Methane in Nitrogen





# Attenuation: Methane in Nitrogen

